BRITISH WELDING * RESEARCH ASSOCIATION

VOL. 5. APRIL, 1951 No. 2

WELDING RESEARCH

PRICE FIVE SHILLINGS

Published by
THE BRITISH WELDING RESEARCH ASSOCIATION · 29 PARK CRESCENT · LONDON W.1

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ASSOCIATION NOTES

Research Report on "Development of a 600-Ampere Argon-Arc Torch for the Manual Welding of Thick Aluminium Alloy Plate"

There are several advantages in using a close square butt edge preparation for welding aluminium alloy plate. Welding speeds are higher than with a vee type preparation and less filler metal is required. Certain work for the LM.1 Committee of the Association required that welds be made in plate of $\frac{1}{4}$ in. thickness and over. With the argonarc equipment, available commercially, which had a maximum capacity of about 300 amps., it was just possible to prepare single pass welds in $\frac{1}{4}$ in. material if preheating was employed. However, preheating is an undesirable complication in research work and is often difficult to employ in practice. It was decided therefore to design and make a torch which would handle much higher welding currents. The torch has a water-cooled metal nozzle and is constructed so that the tungsten electrode can be changed from the back of the torch without disturbing the nozzle. Electrodes of up to $\frac{1}{2}$ in. diameter can be fitted, but $\frac{3}{8}$ in. diameter is the largest size that has been used as yet. Single pass welds have been made in plate up to 1 in. thickness and the torch appears to be very satisfactory in operation.

The work described in this report was prepared for the LM.1 Committee of the British Welding Research Association

on Fusion Welding of Aluminium Alloys, the Members of the LM.1 Committee were as follows:

J. R. Handforth (*Chairman*)	Birmetals Ltd.
W. A. Baker	British Non-Ferrous Metals Research Association.
H. Brooks	Ministry of Supply.
J. E. Chard	Admiralty.
E. Davis	Imperial Chemical Industries Ltd.
G. Haim	Rediweld Ltd.
I. H. Hogg	Ministry of Supply.
H. T. Johnson	Admiralty.
H. Lackenby	British Shipbuilding Research Association.
J. R. Lancaster	Aluminium Plant and Vessel Co.
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W. K. B. Marshall	Rockweld Ltd.
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Dr. E. C. Rollason	Murex Welding Processes Ltd.
R. R. Sillifant	British Oxygen Co. Ltd.
W. S. Simmie	Pressed Steel Co. Ltd.
Major P. C. Varley	British Aluminium Co. Ltd.
J. P. Wadling	Swan, Hunter & Wigham Richardson Ltd.
Dr. E. G. West	Aluminium Development Association.
Dr. J. G. Whitman	Ministry of Supply.
Dr. C. Wilson	High Duty Alloys Ltd.

Technical Secretary L. W. Kastell.

A Review of "Machine Characteristics for Flash Welding of Light Alloys"

The joining of aluminium and aluminium base alloys by resistance flash welding has until recently been considered a very difficult if not impossible process. It has now been shown, however, in the U.S.A. and this country, that flash welding is both possible and practicable. This review was initially prepared some eighteen months ago to summarise existing published information and to encourage interest in the application of the process. Subsequently, valuable research work has been completed by Hess and his associates at the Rensselaer Polytechnic Institute (U.S.A.) which has greatly added to the knowledge of flash welding. Only the initial results of these researches are included in the review, but a more complete acknowledgment will be made in a subsequent report.

Many of the published research reports on flash welding are of American origin, but the lack of data from British sources must not be taken as an indication of the absence of development in this country, e.g. the use of flash welding in window frame and bicycle rim construction is well established.

The review concludes that the basic differences between flash welding of steel and light alloys are the same as exist for spot welding, i.e. current, time and pressure. High currents, short accurately controlled current duration and accurately controlled upset are essential requirements for the flash welding of light alloys, but in the other extreme there is some evidence in favour of the slow-butt welding process in which a less rigid control may be possible with some materials.

This review was prepared for the LR Committee of the British Welding Research Association on Resistance Welding of Light Alloys. The members of the LR Committee were as follows:

Dr. E. G. West (*Chairman*)	Aluminium Development Association.
R. W. Ayres	Sciaky Electric Welding Machines Ltd.
W. V. Binstead	Northern Aluminium Co. Ltd.
H. Brooks	Royal Aircraft Establishment.
B. Evans	Ministry of Supply.
E. A. G. Liddiard	Fulmer Research Institute.
R. F. Tylecote	Royal School of Mines, Department of Metallurgy.
B. Le Pine Williams	

Technical Secretary J. H. Gameson.

ANNUAL GENERAL MEETING

The Sixth Annual General Meeting of the Association is to be held at the Research Station, Abington, near Cambridge, on Wednesday, 25 July, at 2.15 p.m.

R.68

600-AMP. ARGON-ARC TORCH FOR MANUAL WELDING THICK ALUMINIUM ALLOY PLATE

This report was first issued to Members of the British Welding Research Association as a Confidential Document in August, 1950.

By J. H. COLE, M.Sc.

INTRODUCTION

In a previous report to the LM.1 Committee (LM. 1/15 Progress Report on Argon-Arc Welding Thick Aluminium—5 per cent. Magnesium Alloy Plate), it was indicated that in welding aluminium alloy sections of ¼ in. and ½ in. thickness, best results were obtained when single pass welds were made, preferably using a close butt joint. This required less filler metal, and the welds were free from oxide inclusions. With the Argon-Arc equipment available at that time, the current was limited to just under 300 amps., and it was not possible to weld ½ in. thick plate in the above manner without preheating. As preheating is not always possible, and is difficult to control on large structures, it was considered desirable to develop a welding technique which did not require preheating. This called for the use of higher welding currents for ½ in. plate. Thicker sections would then involve the use of still higher currents.

With this in view it was considered that a torch capable of carrying up to 600 amperes, i.e. double the capacity of the available model, would be a useful advance. While torches of this capacity are in use in America for automatic welding, they are generally regarded as too heavy for manual work.

Preliminary Considerations

(*a*) Ultimately the factor which limits the current carrying capacity of an argon-arc torch is the size of the electrode. From the information available it appeared that a tungsten electrode of ½ in. diameter should carry 600 amps.; however, to be on the safe side the torch should be capable of holding a ⅝ in. electrode.

(*b*) Because of the high currents to be used the torch would have to be cooled. The simplest method of cooling is to circulate water through the handle and body of the torch.

(*c*) In torches up to 300 ampere capacity the argon shield or hood is usually made of some refractory material. However, the thermal stresses are severe, and at 300 amps. the ends fuse and the hoods tend to crack during use. The use of a refractory material limits the design of the nozzle to some extent, as once made it cannot be altered, and if the clearance between the electrode and the hood is small the thermal stresses are greater. Refractory hoods usually have a rough surface finish which may upset gas flow.

These considerations lead to a water-cooled metal hood. Exact information on hood shape appears to be lacking. As any streamlined flow of the argon is completely upset when it comes near the molten tip of the electrode, it was considered sufficient at this stage that the hood should give a uniform distribution of argon around the electrode.

(*d*) A standard welding cable to carry 600 amps. is heavy and fairly stiff. By water cooling the cable it can be reduced considerably in cross section. The water used to cool the body and the hood could also be used to cool the lead.

(*e*) Very little information was available as regards the quantity of heat which would have to be taken away by the cooling water. Owing to loss of heat due to radiation, it was considered reasonable to assume that less than half the heat of the arc had to be absorbed by the cooling water as well as that due to the resistance of the current lead. Calculation on this basis indicated that at 600 amps. a flow of two litres of water per minute (the minimum required to operate the flow relay—*see later*) would give a temperature rise of the order of 40 deg. C.

(*f*) The weight of the torch should be kept to a minimum so as to avoid undue operator fatigue.

MATERIALS

In order to obtain maximum heat and electrical conductivity for best cooling conditions, while having freedom from corrosion troubles, the handle, body and hoods were made of copper. As tubing of the required sizes was not available all sections were machined from solid bar.

The body and the hoods were each made in two sections. The internal baffles to direct the water flow were brazed to

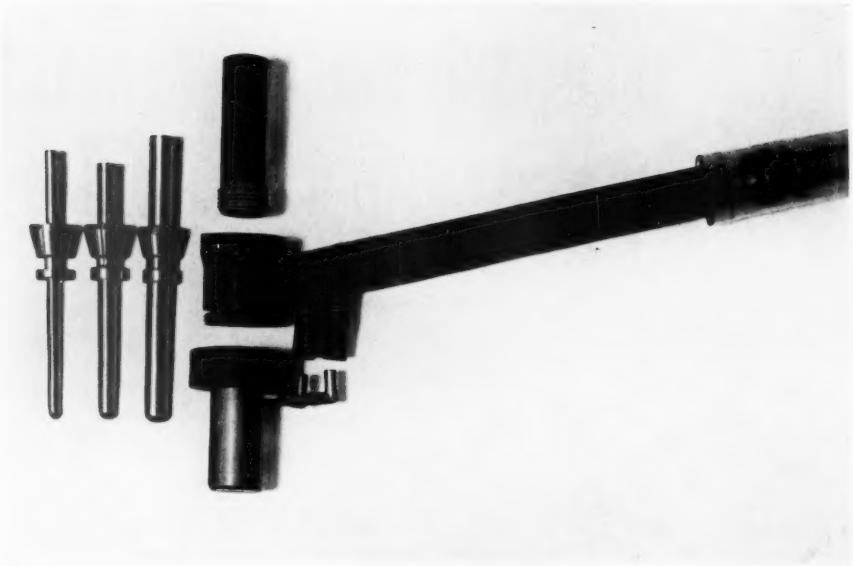

Fig. 1. "Exploded" view of torch.

Fig. 2. Torch assembled for welding.

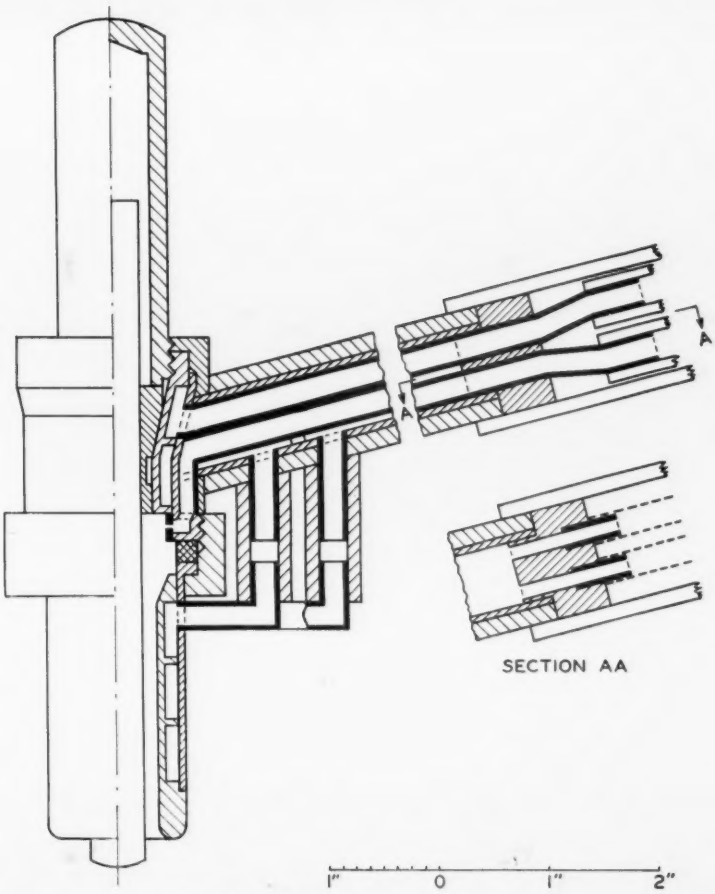

Fig. 3. Sectionalised drawing of torch.

the inner sections, and the water and gas inlet and outlet tubes were brazed to the outer sections. The two sections fit together, and the seams were soft soldered so that there was no danger of melting the brazing metal and displacing the baffles or causing leaks in the water or gas supplies. The handle was soft soldered to the body for the same reason.

To keep the number of cables, etc., leading to the torch to a minimum, the water supply tube, the argon supply tube and the current leads were threaded through an outer tube which serves as a return water tube.

The argon supply tube and the water inlet are of medical P.V.C. tubing, while the outer tube is of transparent P.V.C. tubing. While rubber tubing would probably be suitable, the transparent tube allows the current leads and supply tubes to be seen in order to ensure that there are no kinks in the supply tubes or air bubbles in the outer tube. Any air bubbles in the outer tube could cause hot spots in the supply leads.

The water cooled current lead consists of two copper braids (192 strand by 36 S.W.G. by 9 ft. long) in parallel. These were soft soldered to terminal tubes at each end.

Resin bonded asbestos was used for the nut connecting the hood to the body and for the insulation of the body and handle, as it was thought that parts near the arc might become fairly hot, too hot to allow the use of some of the plastics which would have been better from the point of view of electrical insulation.

DESCRIPTION OF TORCH

The torch is shown in an "exploded" view in Fig. 1 and as assembled for use in Fig. 2, while Fig. 3 is a sectional drawing of the torch. The junction box at the end of the water-cooled cable is shown in Fig. 4.

The welding current was conducted through a standard 600 amp. welding lead from the transformer to the junction box. This lead was threaded through a rubber tube to give additional insulation necessitated by the use of high voltage high frequency current for stabilising the arc. From the junction box the current passes along two parallel copper braid leads to the end of the torch handle and then through the torch body to the electrode *via* a copper collet. The electrode is held in a split tapered collet, which fits into the body of the torch from the back, a different collet being required for each size of electrode. The top of the torch,

Fig. 4. Junction box.

which is of insulating material, screws into the back of the body, preventing the escape of argon, and at the same time bears on to the electrode collet, forcing it into the body. This ensures good contact between the electrode, the collet and the body of the torch. Changing the electrode or any adjustments to the electrode are carried out from the back without in any way disturbing the argon shield.

The argon, after passing through a flow gauge and gas economiser valve to the junction box, flows through a ¼-in. bore P.V.C. tube to the end of the handle and thence down a 3/16 in. bore copper tube, inside the handle, to an annular space at the bottom of the body of the torch. The argon emerges from the annular space in a radial direction through eight small holes equally spaced round the inner circumference.

The hoods, which are insulated from the body of the torch, have a clearance of 1/16 in. from the electrode over a length of 1½ to 2 ins. and the ends are rounded to prevent sucking air into the argon stream.

A normal floating bobbin and tapered tube type of flow gauge was used. In its original form the maximum flow reading was ten litres per minute; however, by using a brass bobbin of four times the weight, the range was doubled. The gauge was then calibrated by measuring the rate at which the pressure dropped in a vessel of known volume as the gas flowed out through the gauge at a fixed rate.

The water enters the junction box through a ¼ in. reinforced hose and then passes through a ¼ in. bore P.V.C. tube and a 3/16 in. bore copper tube to the body of the torch. After circulating twice round the body, the water passes into the handle, and here a baffle directs the water into the hood *via* a rubber tube. According to the size of the hood, the water circulates two or three times and then passes back to the handle, on the opposite side of the baffle, and out of the end of the handle through two ⅛ in. bore copper tubes. These small tubes also act as the terminals of the current leads. The water then flows through the outer transparent tube to the junction box and then through a water flow relay to waste.

The water flow relay can be connected into the contactor circuit of the welding transformer so that it cannot operate unless water is flowing. This eliminates the necessity of having a fuse in the circuit to protect the water-cooled lead.

As a considerable amount of radiant energy is given off from the arc and the work piece, a radiation shield is attached to the handle to protect the operator's hand. This was made of 22 S.W.G. duralumin sheet.

The weight of the torch is approximately 2 lbs. without the lead.

OPERATING CHARACTERISTICS

The torch can be easily and conveniently handled by one hand, leaving the other hand free to manipulate filler rods if required. It is possible that the weight of the torch could be reduced by decreasing the thickness of the various sections or by using an aluminium alloy instead of copper. This latter suggestion may give rise to corrosion troubles where the copper conductor is connected to the aluminium.

If available, smaller bore tubing could be used for the outer tube carrying the return water and sheathing the water and gas inlet tubes and the current leads. This would make the whole lead lighter and a little more flexible.

Owing to the limitations of the transformer capacity in the B.W.R.A. Laboratories, the maximum current used in the torch has been 500 amps. for short periods only. Trial welds have been made using 450 amps. and the torch has performed as anticipated. The rise in temperature of the cooling water was 14 deg. C. with a water flow of 2·2 litres per minute. This is within the calculated temperature rise. As water can flow through the torch at a rate of over ten litres per minute, ample cooling is provided. The water flow relay can be adjusted to cut in at any desired rate of flow above two litres per minute.

The end of the hood near the tip of the electrode remained quite cold, and any spatter or oxide which may deposit on the hood can be readily wiped off.

It has been found that with a current of 450 amps. a tungsten electrode of ⅜ in. diameter, slightly reduced at the end, is satisfactory, but with higher currents and larger electrodes, the molten tungsten on the surface of the electrode drops into the weld pool. The maximum size of tungsten electrode which can be used will depend to some extent on the purity of the tungsten, and will be different if a series condenser is used in the circuit. Further experiments are required to establish these conditions.

Carbon electrodes have also been used, and from preliminary experiments appear to be satisfactory for these high currents. They are, however, fairly fragile.

Fig. 5 is a photograph and Fig. 6 a macro-section of a weld in 1 in. thick AW.10 plate made with a single pass, without preheat, at a speed of 1⅓ in. per minute; current 450 amps.; ⅜ in. tungsten electrode; ⅛ in. diameter aluminium-5 per cent. silicon filler rod; argon flow 17 litres per minute; edge preparation U-groove with ⅜ in. land close butted.

Fig. 7 shows a fillet weld in 1 in. thick AW.10 plate. In order to minimise the undercutting which is normally obtained at the beginning of the run, the weld was commenced 2 in. from the start of the run, then laid backwards for 2 in. and from this point forwards, without a break, for the total length of the run. Current 350 amps.; ¼ in. tungsten electrode; ⅛ in. diameter aluminium-5 per cent. silicon filler rod; argon flow 10 litres per minute; speed 2 in. per minute.

CONCLUSIONS

(1) A manual torch capable of carrying up to 600 amps. has been constructed.

(2) Experimental butt and fillet welds have been made in 1 in. aluminium alloy plate using a single pass technique.

(3) It would appear that there is a limit to the size of tungsten electrode which can be used without giving tungsten inclusions in the weld.

(4) Carbon electrodes can be used in larger sizes for the higher currents.

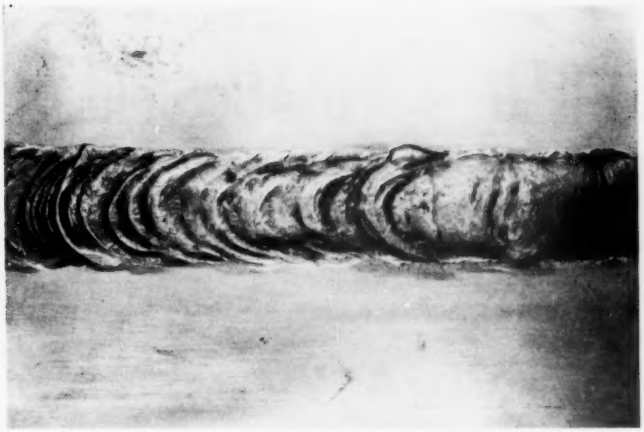

Fig. 5. Butt weld in 1 in. aluminium alloy plate. $\times \frac{1}{2}$.

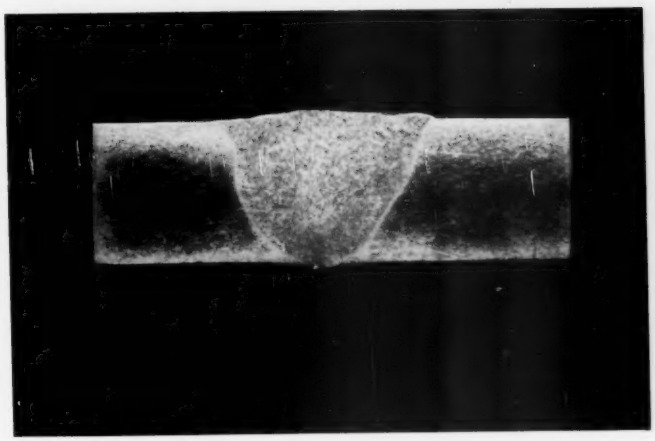

Fig. 6. Macrosection of weld—*actual size*.

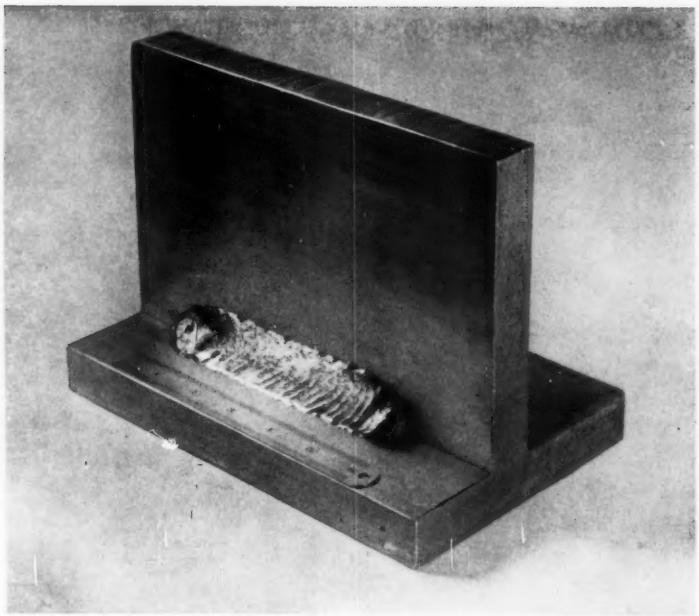

Fig. 7. Fillet weld in 1 in. aluminium alloy plate.

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MACHINE CHARACTERISTICS FOR FLASH WELDING ALUMINIUM ALLOYS

A review, with particular reference to the effect of the material properties on the process, and the design of the flash welding machine.

This report was first issued to members of the British Welding Research Association as a confidential document in July, 1950.

By H. E. DIXON, M.Sc., A.I.M., and
J. H. GAMESON

I. SYNOPSIS

This review was prepared for the L.R. Committee of B.W.R.A. on the Resistance Welding of Light Alloys to provide a summary of existing information on the flash welding of light alloys; with particular reference to the properties of light alloys and their likely effect on desirable machine characteristics. Much of the information is taken from American literature and relates to the flash welding of 14S, 24S, 52S, 53S, 61S, and 75S alloys. Most of the equivalent British Specifications are included in Table II for purposes of comparison.

II. INTRODUCTION

The main problems arising from the flash welding of light alloys fall under the following headings:

(i) The material and the way it is affected by the welding operation.

(ii) The machine and its control.

Up to the present time little information of a fundamental nature on this process has been available,* possibly due to the difficulty of carrying out a systematic study of the many variables which affect the process.

This review has therefore been prepared, basically with the idea of providing a background of available published information on the two major problems outlined above, and as part of the preliminaries for a proposed programme of fundamental research.

III. SUMMARY OF PROCESS

The flash welding cycle may be divided into three parts, preheating, flashing and upsetting. In certain applications a fourth, post-heating (for the purpose of heat treatment) may be introduced, but very few machines have this latter refinement.

The initiation of the welding cycle for flash welding consists of bringing the work-pieces together under light pressure and starting the electrical current flowing. Contact is established at isolated points on the abutting faces, causing these high current spots to melt away and partially vaporising the metal at these areas. The flashing action continues in an explosive manner, and to maintain this action the work-pieces must be moved steadily forward, as the material is burnt off. At the same time heat is being conducted back along the work-pieces, establishing a plastic zone behind each face.

The flashing action is all-important, and to ensure that adequate upsetting results, with expulsion of overheated and oxidised material, etc., the plastic range behind the flashing faces must be of the required depth. Too steep a temperature gradient will cause a cold weld, i.e. temperature of interface may be too low for satisfactory welding, while too great a depth of plastic area will bring about excessive deformation of the component on upset.

The welding operation is completed by the upsetting stroke, which accelerates the forward movement of the work-pieces, bringing the faces under considerable pressure.

The current is switched off (the timing of which, in relation to application of upset, is of importance with certain types of materials), and the weld is forged and consolidated, squeezing all molten metal, overheated metal and oxides away from the interface to promote trans-interface crystallisation.

Fig. 1 illustrates some of the machine variables and material allowances referred to in the text.

IV. METALLURGICAL CONSIDERATIONS

In this section an account is given of the properties of light alloys of known importance in the flash welding process. Comparison is drawn whenever possible between light alloys and mild steel, the latter being readily welded by this process.

This should provide a clearer picture of the particular machine characteristics required to give optimum weld properties in light alloys.

Many of the difficulties in the past have originated from the use of machines which were not designed specifically for aluminium alloys in which proper regard for their particular characteristics could not be taken. The effect of these properties on the technique of flash welding is examined in the following discussion:

(a) *Oxygen Affinity*

(1) **The Problem.**—Light alloys are characterised by the presence of an extremely adherent and refractory surface oxide. This natural oxide film shows considerable variability in thickness and consequently in electrical resistance. Its removal prior to flash welding is recommended by Della Vedowa and Reynolds [6] to reduce contact resistance between material and dies and to reduce the

* Since the circulation of this report to members of the B.W.R.A. in July, 1950, further research investigations into the process and articles on the increased industrial use of light alloy flash welding have been published. A review of this literature is now in course of preparation.

possibility of oxide entrapment at the weld interface. (Reviewers' Note: It is possible that the removal of oxide will promote a more uniform flashing particularly in material of large cross section, and this would tend to reduce the possibility of oxide entrapment at the weld interface.) Three per cent. hydro-fluoric acid solution has been used, although other mechanical or chemical methods suitable for spot welding should be equally satisfactory.

Aluminium alloys oxidise very rapidly at high temperatures and the oxide produced is virtually insoluble in aluminium. It has been shown by Curran and Becker[3] and Hess and Winsor[5] that when an oxide film is present in a light alloy flash weld, low joint efficiencies are generally obtained, and it is impossible to obtain any strength improvement on heat treatment (solutionising and ageing). Rapid oxidation during the flashing cycle is inevitable, and it is not possible to reduce oxide formation during flashing to the same extent as is possible in steel flash welding. Della Vedowa and Reynolds[6] were unable to reduce oxide formation during welding even by the use of inert atmospheres, probably due to the difficulty of completely drying the argon and helium used, and because of the high affinity of oxygen for aluminium.

Rietsch[26] describes differences in the nature of the flashing action which he ascribes to the higher thermal conductivity of aluminium alloys. The flashing action is coarser, the craters are deeper and air can remain in constant contact with the flashing surfaces. There is no protective atmosphere produced during flashing as with steel, and the high temperature and high affinity of aluminium for oxygen results in excessive oxidation. He suggests the use of hydrogen as a protective atmosphere during flashing.

(2) **The Solution.**—Extensive researches on the fatigue strength of flash welded mild steel by Kilger[24] have shown that the quality of a steel flash weld depends on the oxide contained at the interface, and that the presence of oxide depends mainly on the magnitude of the upset pressure, velocity of upset and temperature distribution at the interface, i.e. factors affecting both *oxide formation and expulsion* from the welded joint. Curran and Becker[3] state that for light alloys the upset cycle is the only satisfactory means of oxide removal since the oxygen content of the weld determines weld quality and the upset cycle (upset force, upset velocity and upset distance) can be considered the most critical variable. The main process variables of flashing time, flashing distance and power level affect the removal of oxide only so far as they influence the nature and amount of upset travel, i.e. in their effect on temperature gradient.

Della Vedowa and Reynolds[6] emphasise the importance of work piece dimensions in this respect since oxide elimination is more readily obtained from tube than from bar material.

Excessive oxidation can occur if the flashing current is cut off too early before upset according to Hess and Winsor.[5] Accurate timing of current cut off is also required to avoid over-ageing which is produced if excessive heating occurs at upset. (Hess and Winsor,[5] Curran and Becker,[3] Della Vedowa and Reynolds.[6]) This matter is referred to in Section V (*c*).

Rapid closure on upset is recommended (Curran and Becker[3]) since it reduces the possibility of oxidation after the current cut off, and leads to rapid elimination of molten and plastic material from the weld line. The sudden fall in temperature thus produced is associated with less over-ageing. Curran and Becker[3] show that the complete elimination of oxide from the weld line with material in the annealed condition is difficult and do not recommend flash welding alloys in this condition if welds of high quality are required. Rietsch claims that the use of a protective gas, e.g. hydrogen, during flashing prevents oxidation, and that high upsetting pressures are required only for the elimination of deep craters produced during flashing. Mention is made of the need for upsetting pressures equal to or greater than those used for steel.

(b) Physical Properties

Data on thermal conductivity, specific heat, electrical resistance, etc., are given in Table I, and comparison is made with similar properties for low carbon and medium carbon steel. It will be seen that variation in properties within alloys in the aluminium group is relatively small, and it would be expected that the power requirements for flash welding should not vary much for the materials quoted, but will be much greater than those of mild steel. The high thermal and electrical conductivity should be noted.

Since most of the welding heat is derived from the flashing cycle (formation and explosive rupture of liquid metal bridges), the use of high power level and short flashing time is desirable to reduce conductivity losses, i.e. to establish steep temperature gradients and thus economise in energy requirements.

Table I. Comparison of the Physical Properties of Aluminium Alloys and Steels

B.S. 1470-77	Melting Range	Density gms./cm.^{3} at 20 deg. C.	Coefficient of Linear Expansion 20 deg.-100 deg. C.	Electrical Resistivity (microhms per cm. cube)	Thermal Conductivity C.G.S. Units	Specific Heat 0 deg.-100 deg. C
IC	659-660	2·71	24×10^{-6}	2·9	0·54	
N2	565-577	2·65	22×10^{-6}	4·7	0·37	
N21	565-625	2·65	22×10^{-6}	4·7	0·34	
N3	643-655	2·74	23×10^{-6}	3·9-4·9	0·36-0·42	
N4	593-649	2·70	24×10^{-6}	4·6-4·9	0·35-0·38	
N5	600-640	2·65	23×10^{-6}	5·4-5·7	0·32-0·34	
N6	580-635	2·65	23×10^{-6}	6·4-6·5	0·28	
N7	540-630	2·63	23×10^{-6}	6·2	0·25	
H9	580-660	2·70	23×10^{-6}	3·3-3·5	0·47-0·48	0·23 (approx.
H10	570-660	2·70	23×10^{-6}	3·4-3·8	0·43-0·48	for all alloys)
H11	600-650	2·75	24×10^{-6}	4·5	0·35-0·37	
H12	600-650	2·75	22×10^{-6}	4·05	0·40	
H13	600-650	2·77	24×10^{-6}	4·0	0·37	
H14	530-610	2·80	22×10^{-6}	5·1	0·35	
H15	530-610	2·80	22×10^{-6}	4·8	0·36	
H17	530-640	2·79	23×10^{-6}	5·05	0·40	
H18	530-640	2·75	22×10^{-6}	4·4	0·36-0·43	
Low C. steel (0·06 C, 0·38 Mn)	—	7·87	$14·72 \times 10^{-6}$ (0-800 deg. C.)	13·0	0·156 (0 deg. C.)	0·115 (50-100 deg. C.)
Medium C steel (0·23 C, 0·64 Mn)	—	7·86	$12·64 \times 10^{-6}$ (0-800 deg. C.)	16·9	0·124 (0 deg. C.)	0·116 (50-100 deg. C.)

Table II.—Nominal Compositions of some American Aluminium Alloys and Related British Specifications § [23]

B.S. 1470 Designation	Alcoa Designation	Cu per cent.	Si per cent.	Mn per cent.	Mg per cent.	Zn per cent.	Cr per cent.	British Equivalents: Specifications, Designations and Selection of Related Commercial Designations		
IC	2S	—	99 minimum	aluminium	—	—	—	SIC* EIC†	A4D* B.S.S. 2L17* 2L16* 2L4* L34†	Noral 2S Alcan 2 B.A. C.P. Kynal P10, etc.
N3	3S	—	—	1·2	—	—	—	NS3*	AW. 3C* DTD. 653* DTD. 213A	Noral 3S Alcan 3S B.A. 60 Hid. 11 Kynal PA. 19
H14 H15	17S 24S	4·0 4·6	— —	0·5 0·6	0·5 1·5	— —	— —	HS14* HS15* HE15† AW15	DTD. 603B* 646B* AW. 15A† DTD. 364B† E and F.*	Noral 26S Alcan 26S B.A. 303 and 352 Dural B and S Hid 66 and 01 Kynal C65 C66
N4	52S	—	—	—	2·5	—	0·25	AW 46* AW 4A† NS 4* and NE 4†	DTD. 634* BSS. L44†	Noral M57S Alcan 57S B.A. 21 B.B.2 M.G.2, etc.
—	53S	—	0·7	—	1·3	—	0·25	—	—	Alcan 55S
—	61S¶	0·25	0·6	—	1·0	—	0·25	—	—	Noral 65S Alcan 65S
—	75S	1·6	—	—	2·5	5·6	0·30	—	DTD. 687 DTD. 683†	Noral M75S Alcan 75S Hid RR77 Dural L

* Sheet. † Extrusions. ‡ Clad sheet. § Related Specifications but not necessarily identical.

¶ There is no commonly used British equivalent of the balanced Mg_2Si alloy, but aluminium magnesium silicide alloys with an excess of silicon are well known and are included in the B.S. 1470 specification as alloy H.10 supplied in sheet or extrusion form.

(c) *Condition of Alloy and Effect of Thermal Cycle*

The wrought light alloys may be classified as work hardening or precipitation hardening alloys. In the former the strength is developed by strain hardening, and in the latter by solutionising and by precipitation hardening. The effect of welding heat is to produce softening in either case, and the flashing cycle should be controlled to reduce the extent of the heat affected zone (Della Vedowa and Reynolds[6]). Heating of metal which is in the precipitation hardening condition will lower its strength, either by re-solution of the precipitate or by coalescence of the precipitate so that it forms comparatively large particles which materially reduce hardness. Two distinct zones are normally present; a softened zone due to coalescence of the precipitate (over-ageing) and a hardened zone near the weld due to re-solution and a subsequent ageing at room temperature.

Unlike mild steel, light alloys are characterised by a relatively wide temperature range in which there is high plasticity and low strength due to the presence of a liquid phase at grain boundaries, i.e. in the zone of incipient or partial fusion. Values of temperature interval between liquidus and solidus are given in Table I. It is possible that the extent of this temperature range for a particular material can affect flash weldability.

The final hardness of a flash weld can be affected also by the upset cycle (Curran and Becker[3]). With machines designed to give rapid flashing velocity and high and rapid upset cycles the molten and plastic material is rapidly eliminated from the weld, thus reducing the temperature of the weld with consequently less over-ageing. The continued application of the upset force can thus give rise to work hardening.*

Hess and Winsor[5] draw attention to the danger of using excessive upset distance, which, whilst eliminating the oxide inclusions can produce inter-granular cracking in Alclad 24-S.T. alloy due to upsetting the metal whilst in a hot short condition. Curran and Becker and others[3,5,6], have shown that the timing of current cut off in relation to upset is important in reducing over-ageing as well as oxide elimination. In the butting of the work piece there is normally a large increase in the current under short circuit conditions. Hess and Winsor[5] showed that simultaneous upset and cut off gave best results, and suggested that less accurate timing would be required if a reduction in power level could be made at start of upset. This was investigated by Curran and Becker[3] who showed that less accurate timing was necessary if the power level was reduced on butting of the flashing surfaces.

Curran and Becker[3] have explained the peculiar behaviour of annealed material by reference to work hardening and deformation properties. It appears that in the upsetting of annealed materials the first part to deform along the weld work-hardens and transfers

* It should be noted that the machine employed by Curran and Becker has two-phase upset; firstly, a very rapid "closure" to end flashing and eliminate oxide, and secondly, a slower or forge cycle.

further deformation to material further from the weld line. The process continues until upset is complete, tending to produce an upset characteristic in which the material flow lines or fibres are generally perpendicular to the weld line. In hardened materials it is suggested that softening due to over-ageing or recrystallisation continues in opposition to the work hardening effect, so that the material at the weld interface can continue deforming until more or less completely extruded, before deformation of material further from the weld interface commences.

Results obtained by Curran and Becker show that there is little difference in welding conditions for different structural alloys in the same gauge and temper. This is an interesting conclusion since the condition of the material has a greater effect than relatively wide composition variations.

The structural alloys welded were 14S, 24S, 52S, 61S and 75S. Details of equivalent British Specifications are given in Table II. Recently issued British Specifications for pure aluminium and the wrought aluminium alloys (B.S. 1470-77) are related to existing B.S., S.T.A.7 and D.T.D. specifications in Table III.

(d) General Requirements

The final weld strength in a given alloy will depend on the time temperature cycle to which the weld and adjacent material have been subjected during the welding sequence, and to the final upsetting action for the elimination of oxide. Kilger[24] and Riley[25] have recognised three general welding conditions for steels corresponding to relatively low, medium and high-power levels. Lower power levels require extensive pre-heating with correspondingly wide heat affected zones. The higher the power level the lower the temperature attained at the interface, and the narrower the heat affected zone, probably because more heat is lost in the more fierce flashing action. The flashing velocity must be increased to balance the increased rate of burn off, and the upset cycle must be accelerated to minimise the time available for oxidation of the weld interface as the gap is closed at the end of the flashing operation.

Curran, Patriarca and Hess[10] have also described extensive temperature measurements taken during light alloy flash welding, and have stated that the secondary voltage used during the flashing cycle has no appreciable effect on temperature distribution or power input during flash welding provided the secondary voltage is sufficient to maintain flashing. Burn off distance is the main factor affecting average temperature of interface and the temperature distribution curves are steeper for faster flashing velocities.

The use of very high power levels are not recommended owing to the danger of producing very deep pits by coarse flashing which are not completely removed during upset. High power levels are useful for the initiation of flashing, but means should be provided for a reduction in power level when uniform flashing has been established to avoid the formation of deep pits. Steep temperature gradients produced by the use of fast flashing velocities will facilitate elimination of oxide during upset. They also point out that where high joint efficiencies are not required, the use of slower flashing velocities should be considered because of the reduced flashing power level.

V. MACHINE DESIGN

The essential parts of the flash welding machine are clamps for holding the work-piece, and means of moving the parts towards one another, dies for leading current into the work-pieces and a suitable source of current.[22]

For welding of light alloys the speed and accuracy of operation demands that all mechanical movements are power operated either by hydraulic, pneumatic or electrical drive, and controllable to a predetermined programme which can be precisely repeated for every weld made.

The feasibility of employing in some cases existing equipment, that is machines primarily designed for welding steel, has been demonstrated by Messrs. Hess and Winsor[5] on the flash welding of 24ST materials.

However, modifications to improve consistency were indicated in their report, and they gave a word of warning in so far as the existing equipment must have sufficient capacity to meet the increased power demands required for welding aluminium components that approach a size similar to steel components.

(a) Types of Machines

The A.C. type of machine, as used for flash welding of steels is, with certain limitations as regards electrical capacity and current control, suitable for flash welding of light alloys. In view of the high peak currents required for flash welding at the time of upset, and the consequential increase in the peak loads taken from the mains, new types have been introduced. It should be noted that there are no detailed results available on the performance of these new types which are, however, of general interest in illustrating possible machine characteristics.

The battery powered light alloy flash welder.[8] This type has the advantage that it lends itself to the demand of a high continuous current flow rather than a single shot of short duration. Whereas an A.C. machine demands a peak load of 500 k.V.A. single phase at low power factor, it is claimed that a maximum line demand of only 18 k.V.A. is required by a battery operated machine to accomplish a weld of the same cross-sectional area. The power pack of such a machine consists of 16 cells each of 8 volts pressure, which are water cooled. The cells are kept by being balanced across a three-phase supply circuit at approximately 90 per cent. power factor, and will deliver a maximum welding current of 38,000 amps. Due to the short duration of the welding cycle required for light alloys, such a high drain does not damage the battery plates. Careful maintenance of the batteries is necessary however to ensure satisfactory operation over long periods.

Another type of machine utilises a motor generator power supply connected to a normal flash welding machine through an Ignitron control panel. This type of machine is fully described in Appendix I. The motor of this machine offers a comparatively stable load to the mains supply.

(b) Machine Components

(1) **Power Control Equipment.**—Due to what appears to be the the critical nature of the control of current cut-off at upset, various methods have been devised to facilitate this control.

In hydraulic actuated machines using the principal of cam operation the current cut-off is normally operated by tongue contacts working off the cams. When the flashing cycle is completed the cams are so adjusted that they immediately break the contacts and thus switch off the power supply.

An electronic timer control has also been devised for this operation, where power cut-off at end of predetermined flashing time automatically initiates the upset force.[18]

In the report by Messrs. Curran and Becker[3] a thyratron heat control station is used for controlling the power level at various times during the welding cycle. A schematic diagram of this control is shown in Fig. 2. Control B is opened a few cycles after flashing has been initiated, thus reducing the power level to a value just sufficient to maintain flashing action. Contact E is opened at the start of upset, reducing the power level to a considerably lower value.

(2) **Clamps and Dies.**—Due to the comparative softness of the materials for welding and the liability to fretting at the dies and clamps, which may lead to rejection on a quality finish job, the material must of necessity be clamped with particular care and efficiency.

Heavy die loads are needed to obtain even current distribution and large covering areas to ensure that material surfaces are not marred.[1]

Die materials are almost invariably copper-base alloys, and the best and most economical selection among these alloys for a particular job will depend on a number of different aspects. Some of these are indicated below:

(i) Surface condition required of work-piece material after welding operation.

(ii) Quantity and rate of production.

(iii) Current density in dies.

(iv) Clamping pressure.

(v) Provisions for "backing up" where (iv) is insufficient.

(vi) Water cooling of dies for production programmes.

(3) **Ancillary Equipment.—Preheating**—This is more extensively used in the flash welding of steels, but it would appear that pre-heating can be resorted to for aluminium component sections which are comparatively large in relation to the capacity of the machine or where low energy levels are used.

The welding current required to initiate flashing may be excessive, therefore by heating the junction region of the work-pieces by electrical resistance the temperature can be sufficiently raised to facilitate and maintain the true flashing action.

It must be pointed out, however, that this pre-heating action on aluminium alloys will cause considerable heat affected zones behind the interface and likelihood of excessive deformation of the workpieces on upset.

Light alloy flash welding machines have been developed which incorporate an automatic pre-heating action,[13] it being so arranged that when contact resistance between the work-pieces is lower than a pre-set value, the pre-heat operation is automatic. After switching on the current, the cold work-piece faces are brought together making electrical contact, a motor-driven platen reverses, breaking the contact and then reverses again bringing the faces back into contact; these reciprocations continue until the faces reach a temperature when contact resistance exceeds the pre-set value.

This system is claimed to have an added advantage over the pressure operated system, in so far as that, using a motor-driven platen, changes in the viscosity of the lubricant in the moving parts of the machine due to temperature changes, do not affect the pre-heat cycle.

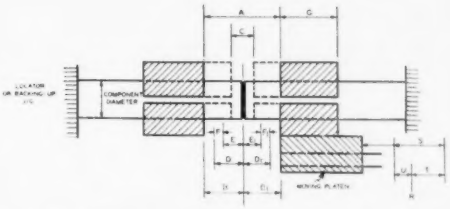

Fig. 1. Schematic diagram of some machine variables and material allowances.

Machine Allowances

G Electrode contact length
S Total stroke (equals $D + D_1$)
T Flashing stroke (equals $E + E_1$)
U Upset stroke ($F + F_1$)
R Release point for upsetting force

Material Allowances

A Initial distance between clamps
B, B_1 Initial overhang of components
C Final distance between clamps
D, D_1 Material lost or welding allowance
E, E_1 Flashing distance
$F + F_1$ Upset distance

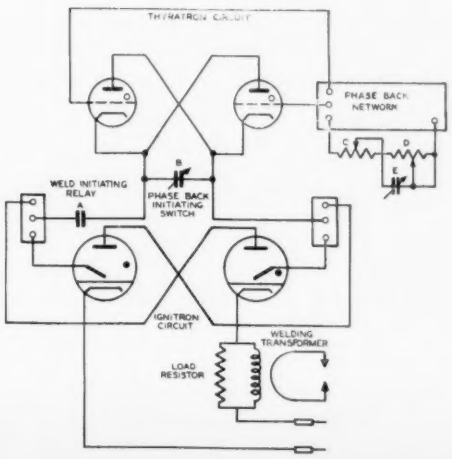

Fig. 2. Current control circuit for flash welding.

(c) Machine Variables

The machine variables which affect the process are set out in the report by Messrs. Curran, Patriarca and Hess.[10]

(1) Secondary voltage.
(2) Flashing distance.
(3) Flashing velocity.
(4) Initial distance between clamps.
(5) Closure velocity.*
(6) Closure distance.*
(7) Upset velocity.
(8) Upset distance.
(9) Upset current duration.
(10) Upset current magnitude.
(11) Final distance between clamps.

The following gives a review of the facts and opinions obtained from examination of the articles and papers appended in the references, so far as they affect these machine variables. The machine variables and material allowances are shown in Fig. 1.

(1) **Secondary Voltage.**—The secondary voltage used during the flashing cycle has no appreciable effect on the temperature distribution set up during flashing as long as it is sufficient to maintain flashing. Also, it has no appreciable effect on the power input to the flash welding machine during flashing.[10]

The amount of welding current required at the start of upset appears to vary between 25,000 to 100,000 amps. per sq.in.[15 14 11].

(2 and 3) **Flashing Distance and Velocity.**—Investigations by Curran, Patriarca and Hess have considerably improved the amount of knowledge available on these variables. The following conclusions are indicated:

(i) That the melting point of the alloy at the flashing faces is not reached until considerable burn-off has occurred.

The shape of the curve they obtained for rise of interface temperature against burn off distance suggested an exponential curve, given by the following equation, as long as the clamps have no effect on the temperature distribution.

$$T_x = T_r + (T_i - T_r)E^{-(V/a)x},$$

where T_x = temperature in degrees Fahrenheit at a point x inches from flashing interface.
T_r = room temperature, degrees F.
T_i = temperature at flashing interface, degrees F.
E = Naperain constant.
V = the velocity of burn off, in./sec.
a = thermal diffusivity of the alloy, sq. in. per sec.

* Variables (5) and (6) describe the initial abutting of the work-pieces after flashing and prior to upset.

(ii) That the average temperature of the interface after a definite amount of burn-off is not particularly affected by the flashing velocity, which would explain in part the different velocities and times used by various authors, all of which give fairly satisfactory results.

(iii) That very high flashing velocities tend to reduce the depth of plastic zone behind the interfaces.

Normal flashing duration appears to vary somewhat and times between two to fifteen seconds are given by various authors.

(4) **Initial Distance between Clamps or Dies.**—For slow flashing velocities in the order of 0·053 in./sec. and flashing distance of 0·34 in., with a clamping distance of 1·76 in., Curran, Patriarca and Hess found that no thermal sink resulted from the dies. The temperature of the work-pieces inside the dies was estimated at 300 deg. F., and it was assumed that the oxide film on the aluminium was sufficient to arrest the heat transfer.

However, for faster flashing velocities increasing the distance (overhang) between clamps gives an increased rise in the interface temperature for similar burn off distances, indicating the considerable heat sink at these flashing velocities.

Distance between clamps.	Flashing distance to obtain melting at interface.
1·7 in.	0·4 in.
2·4 „	0·19 „

Further increase in distance produced no appreciable difference.

These results were prepared to cover this particular variable, and the actual distances used on production work would have to be considered with other variables and conditions.

(5 and 6) **Closure Velocity and Distance.**—Research work carried out by Messrs. Curran and Becker[3] indicate that there would appear to be a distinct advantage in using a very high initial closure speed. A machine designed to incorporate this feature is described in Appendix I.

They considered that rapid initial upset would have the effect of suddenly eliminating the hottest material from the weld line, thereby causing the material within the weld line to have a low average temperature. This, they found, tended to alleviate the critical nature of the time of current cut-off and its magnitude, since less heat was generated in the lower resistivity material presented in the weld zone.

(7 to 11) **Upset Force Velocity and Distance, Power Duration and Magnitude, and Final Distance between Clamps.**—Most designs, especially of American manufacture, appear to favour the high pressure/speed upset, both to reduce the liability of oxidation at the interface and ensure correct temperature gradients. Hess and Winsor have shown that a variation of only two cycles in the time of current cut-off can produce unsatisfactory welds in 24ST aluminium alloy and to obtain reasonably consistent results the cut-off must be accurately timed. (See Fig. 3.) The danger of over-ageing caused by high upset current has led various authors to consider means of overcoming the difficulty, and in one method an almost frictionless platen was used in conjunction with an electronic timer. At the exact moment that the power was cut by the timer, upset was applied by means of tension springs.[18] The results of a machine operating on these lines appeared to be particularly promising.

A slow butting (upsetting) stroke is favoured by one company. On this machine the motor-driven platen gives a forward movement of about $\frac{1}{8}$ in. per second on upsetting, this being in a ratio of either 7 to 1 or 20 to 1 of the flashing speed. In practice this upsetting stroke may take approximately half-a-second, i.e. about 25 cycles to operate, and timing of the current cut-off can therefore be closely controlled. The normal upsetting pressures used are not known, but a table appended to a report by Fisher[13] gives the maximum pressure available at approximately 7 tons.

Of particular interest, in connection with this latter method, are the remarks given by Tylecote on a comprehensive examination of flash welded specimens prepared by the same company on a machine which appears to have a similar method of operation.

His conclusions were that, "the welds submitted seemed to be fusion welds made by a flash welding process. The tensile properties were good, although the elongation in some cases was not as good as would be expected from fusion welds, probably owing to the peculiar nature of the interface between fusion and non fusion zones."[21]

Although the heat sink effect of the dies, etc., has been considered in the section on initial distance between clamps, it should be kept in mind that this effect will be to a certain extent present throughout the process.

The length of a welded component is not normally required to be held to very close tolerances, so the normal procedure is to allow the upset movement to proceed until the resistance of the work-piece to deformation balances the upsetting force.[22]

Control of the final length by means of limited upset must be resorted to where close tolerances on jointed component length are required. Care should be taken when using high-speed machines, such as the hydraulic operated machines on limited upset conditions, as there is the possibility that the platen will rebound when it hits the stop, causing hot-tearing of the material.

VI. CONCLUSIONS

The technique of flash welding light alloys can be said to differ from that of mild steel in much the same manner as it does in spot welding. All three major factors, current, pressure and time, are altered. The following notes taken from various papers indicate this:

Aluminium with its higher conductivity, lower melting point, higher oxidation rate and softness at elevated temperatures requires higher currents, shorter time and faster application of the forging pressure.[11 15]

Timing of current cut-off after upset is not critical in steel because of its higher melting point, but with aluminium a very much greater control must be exercised due to the very short range between forging and melting temperatures.[19]

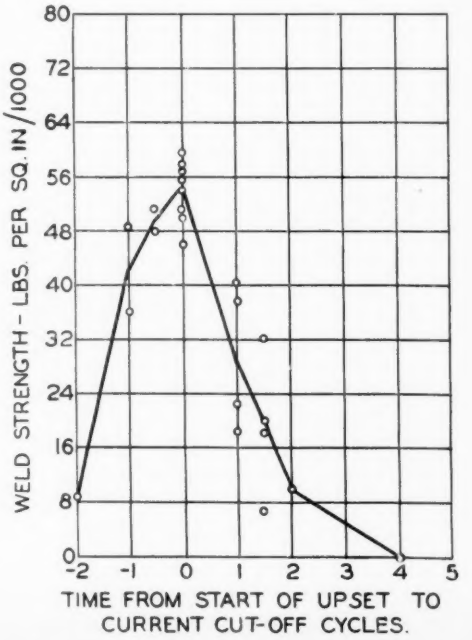

Fig. 3. Effect of timing of current cut-off with respect to upset for 24ST (unclad) aluminium alloy.

The flashing action is not initiated or maintained as readily as in steel welding, and more molten metal may be forced out.[12] Heat loss caused by conduction demands quicker burn off to keep the action going, and the flashing time is generally shorter; this means greater platen velocity and the timing of the upsetting action is more critical. Therefore the weld strength, which is the governing characteristic for any given alloy, will depend both on the time temperature cycle to which the weld and adjacent material have been subjected during the welding sequence, and to the final upsetting action. The raising of the surfaces to welding temperature is dependent on the capacity of the equipment available and the elimination of oxide controlled by the upset cycle of the machine.

Fig. 4 shows the approximate variation of current and platen travel against the time for both an aluminium and steel flash weld.[11]

The main problem is a mechanical one of machine design and the effect of the various machine variables in determining the temperature gradients during flashing and upset. With this information to hand, allowing set-up allowances to be fully tabulated, the simplicity of operation of flash welding combined with the large range of materials and sections which can be welded will give a wide field of application to the process.

APPENDIX I

The machine used at the Rensselaer laboratory[10] has been particularly designed to permit a study of the fundamental variables of the process.

The upset portion is divided into two distinct mechanical phases:

(i) "Closure".—High platen accelerations are possible, ranging up to 5,000 in. per second, with up to 0·1 in. travel. (Both magnitude of acceleration and distance are controlled between these limits.)

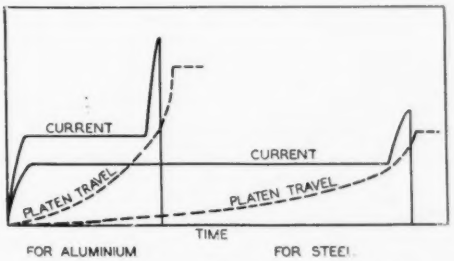

Fig. 4. Plotted current and platen travel against time.

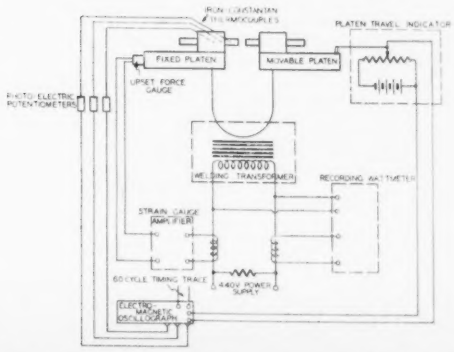

Fig. 5. Schematic drawing of the instrumentation of flash welding machine used at the Rensselaer Institute, U.S.A.

(ii) "Forging" deals with hot forging or upsetting of material at a maximum rate of 2 in. per second compatible with the maximum pressure rating of the machine of 29,400 lbs. However, this can be exceeded by 25 per cent. on occasional operation.

The transformer has eight taps on the 440 volt primary, giving an open circuit secondary voltage, of from 8·2 to 15·7 volts. Ignitron contactors using two type 0 tubes carry the current. Maximum machine capacity is 300 kVA.

The platen travel allows a gap of 4 in. between the clamps, each clamp exerting a maximum load of 3,600 lbs. (Mechanical back-ups are used.)

Control of the hydraulic operated automatic weld cycle is by means of a squirrel cage motor driving a sequence cam shaft through a speed reducer. A spiral cam operating a servo valve controls the oil flow to the main cylinder. An adjustable level linkage between the servo follower valve and the platen controls the platen travel/cam rise ratio and provides a method of controlling the welding power, upset initiation, or any other timing functions needed.

A thyratron heat control station is used for controlling the power level at various times during the cycle, the power supply coming from a 350 kVA single-phase generator driven by a synchronised motor which is located 300 ft. from the welder. This long bus bar provides a power supply with a definite dropping characteristic, and this fact should be kept in mind when using machines with a constant voltage supply.

Records of platen travel and primary current are indicated on an oscillograph. The complete set-up showing the method of determining the temperature distributions existing in the specimen during welding is shown in Fig. 5.

APPENDIX II

The following data and remarks are taken from an Advisory Report on flash welding aluminium by C. B. Smith[20]. This report reviews a survey of existing information on the use of light alloy flash welding in America in 1944.

Section 1.—Smith put forward the following pertinent questions on machine design:

(*a*) What speed range is required for both flashing and upset? What is the shape of the travel, time curve?
(*b*) What upset pressure is needed?
(*c*) What distances will be traversed in both flashing and upset?
(*d*) What is the optimum flashing voltage?
(*e*) How much current (amps./sq.in.) is necessary at any time, flashing or upset?
(*f*) How precisely must upset current be timed in relation to upset travel? Will some special timing device be necessary?

The results of the survey suggested a possible machine design which would contain the following criteria:

250 kVA machine with hydraulic actuation, developing 100,000 amps. (for a 10 volt, open circuit, secondary tap setting) when platens minus clamping fixtures are spaced 1 to 1¼ in. and short-circuited with a 1-in. copper plate.

There should be sixteen transformer taps with a voltage range of 4 to 15 volts, a speed range of one to twenty seconds, and a platen driving force of at least 35,000 lbs.

Provision should be made for easily changing both the cams and oil accumulator capacity for not less than ⅜ in. upset travel. The machine design must allow for the full development of this upset travel and at least 1 to 1½ in. of flashing travel. Finally, all control adjustments should be easy to make and properly calibrated for repetition purposes.

Section 2.—Available data on machine variables taken from four sources of information indicated in each case by the letters A, B, C or D.

(*a*) Electrical capacity:

A—100,000 amps./sq.in. at upset.
B— 80,000 ,, ,, ,, for ⅛ in. thickness.
27,000 ,, ,, ,, ,, ¼ in. ,,
13,600 ,, ,, ,, ,, 9 in. × ½ in. sheet.
C—100,000 ,, ,, ,,
D— 30,000 ,, ,, ,, is ample.

(*b*) Flashing travel:
A—$\frac{3}{8}$ in. for small or thin sections;
$1\frac{1}{2}$ in. for large sections ($\frac{1}{8}$ in. to $\frac{3}{4}$ in. minimum for 9 in. rounds).
B—$\frac{3}{4}$ in. for $\frac{1}{4}$ in. thicknesses, $1\frac{1}{8}$ in. minimum for 9 in. × $\frac{1}{4}$ in. plate.
C—9T up to ·070 in. thick sheet or tube. Decrease ratio until at ·125, use 6T.
D—1 in. to $1\frac{1}{4}$ in. for $\frac{1}{4}$ in. to $\frac{5}{8}$ in.

(*c*) Flashing time:
A—$\frac{1}{2}$ second for small or thin sections.
1 second for large ($\frac{1}{8}$ in. to $\frac{3}{4}$ in. diameter solid).
B—3 to 5 seconds for $\frac{1}{8}$ in. thick sheet. Width 1 in. to 6 in.
$2\frac{1}{2}$ seconds for $\frac{1}{4}$ in. thickness.
5 seconds for 9 in. × $\frac{1}{2}$ in. sheet.
C—$\frac{1}{2}$ to 2 seconds.
D—15 seconds, 35 seconds.

(*d*) Upset travel:
A—$\frac{1}{2}$T—1/16 in. for sheet or tubing (T = thickness, inches).
$\frac{1}{2}$D—1/16 in. for solid rounds (D = diameter, inches).
B—$\frac{1}{4}$ in. for $\frac{1}{4}$ in. thickness, $\frac{3}{8}$ in. for $\frac{1}{2}$ in. thickness.
C—$\frac{1}{2}$T—1/16 in. for sheet or tubing.
$\frac{1}{2}$ in—1/16 in. for solid rounds.
D—$\frac{1}{4}$ in. to $\frac{3}{8}$ in. for $\frac{1}{4}$ in. thickness.

(*e*) Time of upset current:
A—1 to 5 cycles, very important.
B—30 cycles, approx. $\frac{3}{8}$ in. thickness.
60 cycles, approx. $\frac{1}{4}$ in. thickness.
40 cycles, approx. $\frac{1}{2}$ in. thickness.
C—2 to 5 cycles.
D—Current carried well into upset.

(*f*) Upset pressure:
A—20,000 to 30,000 psi.
B—40,000 psi. ($\frac{1}{8}$ in. thickness)—mostly used to overcome platen inertia. 28,000 psi ($\frac{1}{4}$ in. thickness).
C—Maximum upset velocity must be reached in 1-3 cycles.
D—25,000 to 50,000 psi., mostly to overcome table inertia.

(*g*) Final die spacing:
A—1/16 in. for thin sheet, 3/16 in. for $\frac{1}{2}$ in. to $\frac{3}{4}$ in. diameter solid rounds.
B—5/16 in. for $\frac{1}{4}$ in. thickness, $\frac{1}{2}$ in. for $\frac{1}{2}$ in. thickness.
C—1·5T for first sheet and tubing.
D—1·5T for $\frac{1}{4}$ in. thickness (approx.).
$\frac{5}{8}$T for $\frac{5}{8}$ in. thickness (approx.).

Section 3.—The following records were compiled largely from test reports collected in the course of the survey.

(*a*) Flash welding of 24S rod of $\frac{1}{4}$ in. diameter.

Area of cross section	·05 sq.in.
Flashing travel	$\frac{3}{8}$ in.
Upset travel	$\frac{1}{4}$ in.
Primary current	7·5 to 10 amps.
Open circuit secondary voltage	2·0
Mechanical drive—kVA	80

Some of the specimens were tested in the "as welded" condition, while others were heat treated prior to testing. The heat treatment consisted of immersion in a salt bath at 930 deg. F. for thirty minutes, followed by a cold water quench.

Tensile Tests	No Heat Treatment		Heat Treated	
	Ultimate psi	Elongation per cent.	Ultimate psi	Elongation per cent.
24SO to 24SO	30,600	7·0	38,100*	0·0
	29,700	11·0		
	30,200*	5·0		
	31,700*	5·0		
	30,400*	5·0		
24ST to 24ST	64,600*	4·0	45,900*	0·0
	58,600	5·0		
24SO to 24ST	29,700*	0·0	41,300*	0·0

* Broke at weld.

Fatigue Tests: Krause—Gripped $\frac{1}{8}$ in. from weld by stationary jaw.
Gripped 2 to 3/32 in. from weld by movable jaw.
Total deflection ·112 in, 1,725 cycles per minute.

	No Heat Treatment Cycles	Heat Treated
24SO to 24SO	75,000*	217,000 cycles broke in jaws
24ST to 24ST	646,000	378,000 cycles broke in jaws
24SO to 24ST	319,000*	213,000*
24ST parent material	493,000 988,000	

* Broke at weld.

(*b*) Flash welding 53ST material.

Total area	$1\frac{1}{2}$ sq.in.
Open circuit	10·3 volts
Upset pressure	28,300 maximum
Clamp pressure	26,000 lbs.
Total time	$2\frac{1}{2}$ seconds
Amount flashed	$\frac{3}{4}$ in.
Amount upset	$\frac{1}{4}$ in.
Final die opening	5/16 in.

Current continued into upset 60 cycles.
Flash varied from $\frac{1}{8}$ in. to 1 in. without any difference in weld quality.
310 kVA—power factor, 82 per cent.

Note.—The results were considered satisfactory on the basis of micro-specimens, no photomicrograph was available for examination.

(*c*) The settings tabulated below were those giving best results for the joints and machines shown. Information regarding the physical properties is not available. It is believed that tests used consisted of breaking the specimens by bending in the "as welded" condition. A specimen was considered satisfactory if the failure occurred outside the weld.

Description of Joint			Secondary Voltage Open Circ.	Flash		Upset			Size Machine kVA
Alloy	Size and Shape	Area sq.in.		Travel inches	Time seconds	Travel inches	Secondary Cycles	Current Amps.	
24ST Sheet	4 in. × ·040 in.	·160	7·5	15/32	0·75	5/32	4	40,000	250
3SO Sheet	4 in. × ·040 in.	·160	9·2	15/32	1·0	5/32	1	53,000	250
3S½H* Tube	1 in. × 7/16 in. × ·068 in.	·285	6·0	13/32	1·5	3/32	3	34,000	150
3S½H Tube	2 5/16 in. × ·032 in.	·288	6·0	½	1·8	1/8	4	31,000	250
3S½H* Tube	1 in. × ½ in. ·062 in. × 125 in.	·325	4·0	11/32	1·0	1/16	5	20,000	50
52S Sheet	7½ in. × ·050	·375	8·0	3/8	1·0	3/16	4	80,000	300

* Rectangular tube with mitred joint.

(*d*) Flash welding 53S tubing .. 1 5/16 in O.D. × 5/32 in. thick wall

Area of cross section	0·49 sq.in.
Flashing travel	3/16 in.
Flashing time	3/5 second
Upset travel	3/16 in.
Closed dies	1 in.
Mechanical drive	350 kVA
Upset current	Amount and time unknown, but evidence exists that it is of considerable magnitude, since the 550 primary voltage drops to 110 at upset.

In production, test coupons were made about every 200 welds and subjected to bend tests in a vice. The weld must not break to be satisfactory.

(*e*) Flash welding of 17SO bar .. $\frac{3}{8}$ in. × $1\frac{1}{8}$ in.

Area	1·02 sq.in.
Flashing travel	1 in.
Flashing time	15 seconds
Upset travel	$\frac{3}{4}$ in.
Final die opening	$\frac{1}{2}$ in.
Maximum upset	—
Maximum pressure	50,000 lbs.
Upset current	30,000 amps.
Flashing current	12,000 to 15,000 amps.

The specimens were heat treated after welding one hour at 945 deg. F., and quenched in cold water.

No evidence of cracks or porosity were noted in photomicrographs of this welding technique.

Six $\frac{1}{2}$-in. diameter tensile specimens were machined from three sample welds. The results of the tensile tests were:

Sample No.	Specimen No.	Tensile Strength psi	Elongation in 2 in. per cent.
1	1—1	38,000	1·0
	1—2	57,000	9·5
	Average ..	47,900	5·3
2	2—1	44,100	2·5
	2—2	46,400	4·0
	Average ..	45,250	3·3
3	3—1	42,500	2·5
	3—2	46,100	3·0
	Average ..	44,300	2·8

For comparative purposes, a summary of some of the reported mechanical properties of flash welded joints are included.

	As Welded		Heat Treated after Welding		
Alloy	Ultimate strength psi	Joint Efficiency Estimated per cent.	Condition	Ultimate strength psi	Joint Efficiency Estimated per cent.
24ST	64,600	95·0	T	45,900	68
	58,600	86·0			
	30,000	44·0	T	46,000	68
	30,000	44·0	T	42 000	62
	38,000	56·0	T	25,000	37
24SO	30,600	87·0	T	38,100	56
	29,700	84·0			
	30,200	86·0			
	31,700	90·0			
	30,400	86·5			
	24,800*	100·0			
	25,600*	100·0			
	26,200	98·0			
	26,600*	100·0			
17SO	—	—	T	38,000	61
			T	57,800	93
			T	44,100	71
			T	46,400	75
			T	42,500	68
			T	46,100	74
53SW	30,000	90·0			
	34,000	100·0			
	25,000	79·0			
R-301-0	22,600	88·0	T	63,800	95
	25,100	97·0	T	64,200	96
	25,400	98·0	T	64,200	96
	25,600*	100·0	T	64,800	97
	25,800*	100·0	T	63,500	95
	25,700*	100·0	T	56,900	85
	24,900	96·0	T		
	26,600*	100·0			
	25,800*	100·0			
61ST	29,900	66·0			
	30,000	66·5			
	30,000	66·5			
	30,300	67·0			

* Specimens failed in the parent material at appreciable distances from the weld.

Note.—Separations in above groups signify differences in welding technique.

Table III.—British Aluminium and Aluminium Alloy Specifications*

B.S. 1470-77	Related Specifications, not always Identical	
	B.S./S.T.A.7	Others
—	A1	—
E1A	—	—
S1A	A2	—
W1A	—	—
E1B	A3	—
S1B	A3	—
R1B	—	—
W1B	—	—
—	A4A	B.S. 3L31
E1C	A4B	B.S. L34
T1C	A4C	B.S. 4T9
S1C	A4D	B.S. 2L4; B.S. 2L16; B.S. 2L17
R1C	A4F	B.S. L36
W1C	—	—
NW21	AW1	—
—	AW2A	—
—	AW2B	—
NW2	AW2C	—
—	AW2D	—

* A.D.A. Information Bulletin No. 2, 3rd Edition, 1949, "The Properties of Aluminium and its Alloys."

(*continued overleaf*)

Table III (continued)

B.S. 1470-77	Related Specifications, not always Identical	
	B.S./S.T.A.7	Others
—	AW3A	—
—	AW3B	—
NS3	AW3C	D.T.D. 653; D.T.D. 213A
NW3	—	—
NE4	AW4A	B.S. L44
NT4	AW4B	D.T.D. 310C; D.T.D. 440
NS4	AW4C	D.T.D. 634; D.T.D. 606
NW4	—	—
NE5	AW5A	—
NT5	AW5B	—
NS5	AW5C	D.T.D. 180B
NW5	—	—
NE6	AW6A	—
NT6	AW6B	—
NS6	AW6C	—
NW6	AW6D	D.T.D. 303
NR6	AW6D	D.T.D. 303
NE7	AW7A	D.T.D. 297
NF7	AW7A	D.T.D. 297
NT7	AW7B	D.T.D. 186A; D.T.D. 190
NS7	AW7C	D.T.D. 182A
NW7	—	—
—	AW8	B.S. 1080
HE9	AW9A and B	D.T.D. 372
HE10	AW10A and B	—
HF10	AW10A and B	—
HT10	AW10C	—
HS10	AW10D and E	—
HW10	AW10F	—
HE11	AW11A and B	D.T.D. 443; D.T.D. 423B
HF11	—	D.T.D. 443; D.T.D. 423B
HF12	AW12	B.S. 2L40; B.S. L45; D.T.D. 130A; D.T.D. 184; D.T.D. 410
HR13	AW13	D.T.D. 327
HS14	AW15	B.S. 5L3; D.T.D. 603B
HC14	AW15	B.S. 2L38; D.T.D. 390; D.T.D. 610B
HT14	AW15	B.S. 5T4; D.T.D. 173
HE14	AW15	B.S. 6L1; B.S. 2L39
HF14	AW15	D.T.D. 147; D.T.D. 150A
HR14	AW14	B.S. 2L37
HE15	AW15A and B	B.S. 6L1; B.S. 2L39; B.S. 2L40; B.S. L45; D.T.D. 364B
HF15	AW15A and B	B.S. 2L40; B.S. L45; D.T.D. 147; D.T.D. 150A; D.T.D. 364B
HT15	AW15C and D	D.T.D. 464A; D.T.D. 520
HS15	AW15E and F	B.S. 5L3; D.T.D. 603B; D.T.D. 646B
HC15	AW15G and H	B.S. 2L38; D.T.D. 546B; D.T.D. 610B; D.T.D. 390
HR15	—	—
—	AW16A	D.T.D. 363A
—	AW16B	—
—	AW17A	B.S. 4725
HF17	AW17B	B.S. 4L25
HF18	AW18	B.S. 2L42

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Printed in England by Lawrence Press Ltd. Henry Road, New Barnet, Herts